High precision Standard Model predictions for V+jet decay coefficients for LHC

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Electroweak Precision Physics from Beta Decays to the Z-pole
MITP, October 27, 2022

[0] *in collaboration with:* R. Frederix, M. Pellen, R. Poncelet, A. Popescu

Today's talk

1. Status for high precision matrix-element generators
2. Decay coefficients for V+jet
3. Z+jet at NLO EW
4. W+jet at NNLO QCD+NLO EW

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An overview of current matrix-element generators for LHC physics

- Some open-source matrix-element generators:

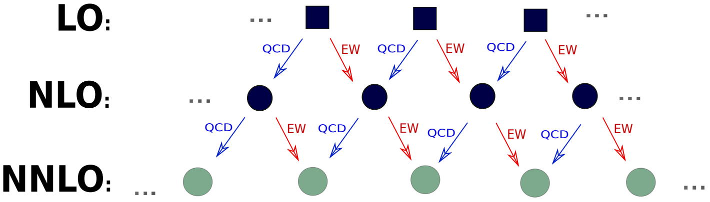
MEG	auto.	NLO QCD	NLO EW	matching NLO QCD	matching NLO EW
COMIX	YES	YES	NO	Sherpa	NO
MCFM	NO	YES	NO/YES	NO	NO
AMEGIC++	YES	YES	NO	Sherpa, Herwig	NO
AlpGen	NO	NO	NO	Herwig, Pythia	NO
MadGraph5_aMC@NLO	YES	YES	YES	Herwig, Pythia	NO

- **No automated matching for NLO EW**
- **No fully-automated NNLO QCD**
- Main focus in matrix-element group in Lund:

$$\underbrace{\text{MadGraph5}}_{\text{Feynman graph}}\_\underbrace{\text{a}}_{\text{automated}}\underbrace{\text{MC@NLO}}_{\text{matching method}}$$

Standard Model perturbation theory

- The perturbative tower of $SU(3) \times SU(2) \times U(1)$
- Expansion in coupling constants: α_s (strong) and α (electroweak)



- **That's all fixed-order!**

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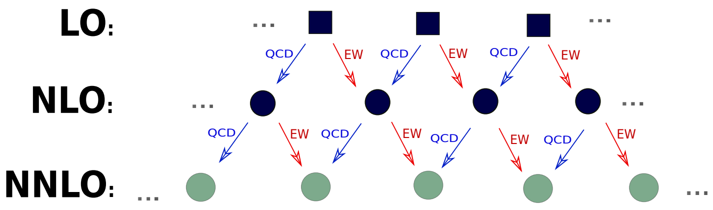

- **That's all fixed-order!**
- In connection with each blob, there are logarithms of the type

$$\alpha_s^n \log^{2k}(\mu_1/\mu_2) \quad , \quad 1 < k < 2n \tag{1}$$

with μ_1, μ_2 two scales of the process

- In regions of phase space where logarithms are small, fixed-order expansion works!
- Where the logarithms are large, we need **resummation** or **parton showers**
- But at highest orders (NNLO QCD, NLO EW), automated matching to parton showers not available yet!

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The V+jet process

- One of the key processes for measuring EW parameters (m_W) at LHC:

$$pp \to V + \text{jet} \to l_1 l_2 + \text{jet}$$

  (V=Z,$W^{\pm}$)
- Total cross section at LHC 13 TeV for V+jet production: $\sim$ 12000 pb

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- Total cross section at LHC 13 TeV for V+jet production: $\sim$ 12000 pb
- Expansion of process to NNLO:

$$\begin{aligned}
\Delta_{\mathrm{LO}}(\alpha_S,\alpha) &= \underbrace{\alpha_S\alpha^2\Delta_{1,2}}_{\mathbf{LO_1}} + \underbrace{\alpha^3\Delta_{0,3}}_{\mathbf{LO_2}} \\
\Delta_{\mathrm{NLO}}(\alpha_S,\alpha) &= \underbrace{\alpha_S^2\alpha^2\Delta_{2,2}}_{\mathbf{NLO_1}} + \underbrace{\alpha_S\alpha^3\Delta_{1,3}}_{\mathbf{NLO_2}} + \underbrace{\alpha^4\Delta_{0,4}}_{\mathbf{NLO_3}} \\
\Delta_{\mathrm{NNLO}}(\alpha_S,\alpha) &= \underbrace{\alpha_S^3\alpha^2\Delta_{3,2}}_{\mathbf{NNLO_1}} + \underbrace{\alpha_S^2\alpha^3\Delta_{2,3}}_{\mathbf{NNLO_2}} + \underbrace{\alpha_S\alpha^4\Delta_{1,4}}_{\mathbf{NNLO_3}} + \underbrace{\alpha^5\Delta_{0,5}}_{\mathbf{NNLO_3}}
\end{aligned} \tag{2}$$

Decay coefficients

- **Differential cross section** (5-dimensional) in V-boson kinematics expanded in **real spherical harmonics**

$$\frac{d\sigma}{dp_{T,Z}dy_Z dm_{ll}d\Omega} \propto \Big((1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + A_2\frac{1}{2}\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big) \tag{3}$$

  with eight **angular/decay coefficients** $A_i(p_{T,V}, y_V, m_{ll})$
- This decomposition separates production mechanism and decay part
- Angles (θ,ϕ) are angles of $l^{\pm}$ in the **Collins-Soper frame**

Current status of V+jet decay coefficients at high energies

Z + jet

- **Theory:**
  1. NNLO QCD[1]
  2. NLO QCD+PS[2]
- **Measurements:**
  1. CDF: $\sqrt{s}$=1.96 TeV[3]
  2. CMS: $\sqrt{s}$=8 TeV[4]
  3. ATLAS: $\sqrt{s}$=8 TeV[5]
- **Wishlist:**
  1. NLO EW , NNLO QCD+PS
  2. 13 TeV run results + lower uncertainty

W + jet

- **Theory:**
  1. NLO QCD+PS[6]
- **Measurements:**
  1. CDF: $\sqrt{s} = 1.8$ TeV[7]
  2. Predictions by unfolding from Z+jet[6]
- **Wishlist:**
  1. NNLO QCD, NLO EW , PS matched
  2. Direct measurements for LHC energies

[1] R. Gauld et al. arXiv:1708.00008
[2] A, Karlberg et al. arXiv:1407.2940
[3] CDF Collaboration arXiv:1103.5699v3
[4] CMS Collaboration arXiv:1504.03512
[5] ATLAS Collaboration arXiv:1606.00689
[6] ATLAS Collaboration arXiv:1701.07240
[7] CDF Collaboration arXiv:hep-ex/0504020

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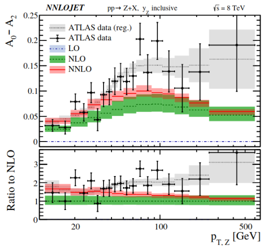
Decay coefficients for Z+jet: Lam-Tung relation

- Up to order $\boldsymbol{\alpha_S\alpha^2}$ **(LO): Lam-Tung relation** $A_0 = A_2$ (if $\Phi_1 = 0$)

$$A_0 = \sin^2\theta_1 \quad , \quad A_2 = \sin^2\theta_1 \cos 2\Phi_1 \tag{4}$$

  (θ_1, Φ_1 are the angles of the incoming parton)

- Predictions for Z+jet available at order $\boldsymbol{\alpha_S^3\alpha^2}$ **(NNLO QCD)**[8]
- ATLAS and CMS (and runs at Tevatron) all measured **higher violation** of Lam-Tung than predicted by NNLO QCD at $p_{T,Z} > 20$ GeV



[8] R. Gauld, *et al.* High Energ. Phys. 2017, 3 (2017)

Decay coefficients for Z+jet: setup

- **This project**: Calculate electroweak corrections to the dominant angular coefficients and Lam-Tung relation
- **Fixed-order**: $pp \to \{e^+e^-, \mu^+\mu^-\} + j$ at 8 TeV with MadGraph5_aMC@NLO at

$$\text{NLO QCD+EW} := \text{LO}_1 + \text{LO}_2 + \text{NLO}_1 + \text{NLO}_2$$

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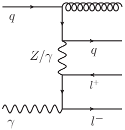
$$\text{NLO QCD+EW} := \text{LO}_1 + \text{LO}_2 + \text{NLO}_1 + \text{NLO}_2$$

- Introduce **single lepton p_T cut** to avoid double IR (2-loop) singularity $\to$ vary cut to extrapolate to the full phase space of the dilepton pair



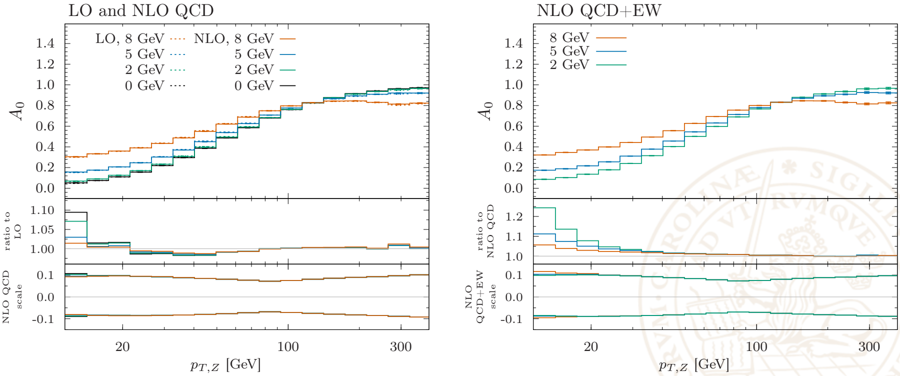
- Use moments method for each coefficient in $A_i f(\theta, \Phi)$

$$A_i \propto \frac{\int \mathrm{d}\Omega \mathrm{d}\sigma f(\theta,\Phi)}{\int \mathrm{d}\Omega \mathrm{d}\sigma} \tag{5}$$

- **Note!** Due to the ratio-nature of the coefficients, EW Sudakovs are not necessarily expected to show up!

Decay coefficient for Z+jet: results

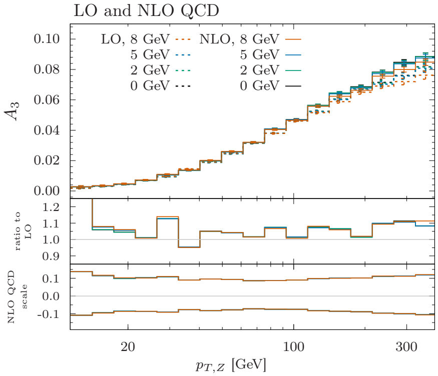
- $p_{T,Z}$-distributions for $\boldsymbol{A_0}$ at
  LO and NLO QCD (left) and NLO QCD+EW (right)
- Negligible electroweak corrections **except in low-$p_{T,Z}$ region**

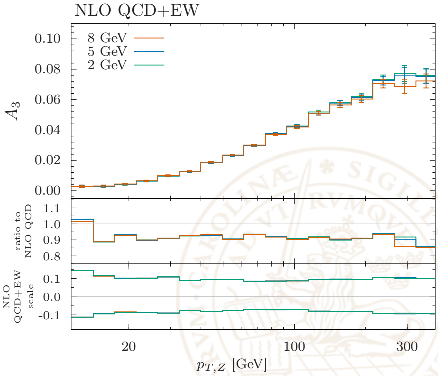


[9] R. Frederix, T. Vitos. arXiv:2204.12394

Decay coefficients for Z+jet: results

- $p_{T,Z}$-distributions for $\boldsymbol{A_3}$ at LO and NLO QCD (left) and NLO QCD+EW (right)
- Constant -10% electroweak corrections





[9] R. Frederix, T. Vitos. arXiv:2204.12394

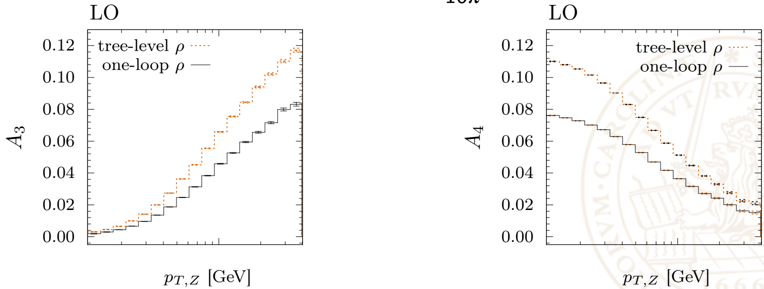
Decay coefficients for Z+jet: results

- Electroweak input parameters important for A_3 and A_4!
- ρ-parameter entering

$$\sin\theta_w^2 \to \sin\theta_w^2 + \Delta\rho\cos\theta_w^2 \tag{6}$$

needs to be consistently included in LO and NLO QCD
$\to$ include one-loop contribution [10]

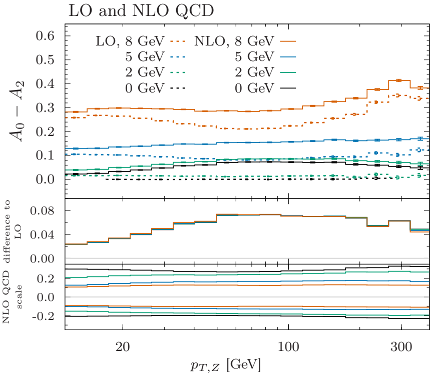
$$\Delta\rho^{(1)} = 3m_t^2\frac{\sqrt{2}G_\mu}{16\pi^2} \tag{7}$$

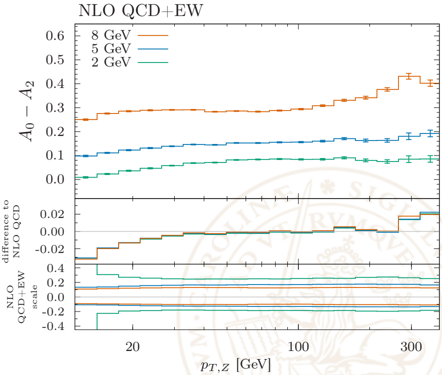


[10] J. Fleischer, *et al.*, 10.1016/0370-2693(93)90810-5

Decay coefficients for Z+jet: results

- Lam-Tung violation $A_0 - A_2$ at
  LO and NLO QCD (left) and NLO QCD+EW (right)





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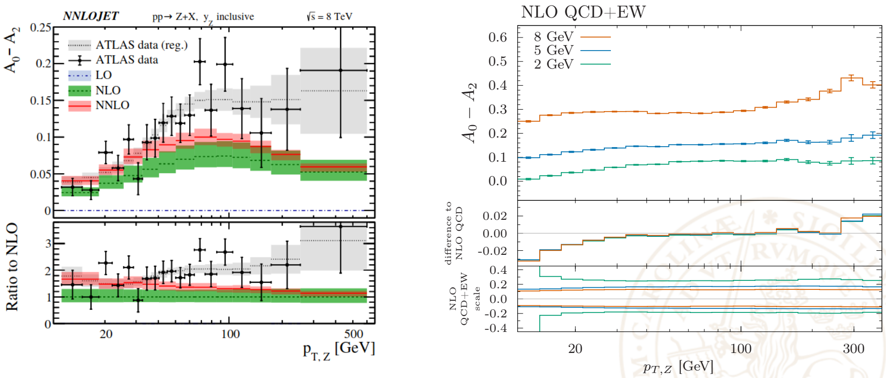
9 R. Frederix, T. Vitos. arXiv:2204.12394

Decay coefficients for Z+jet: results

- Lam-Tung violation $A_0 - A_2$ at NNLO QCD with ATLAS data (left)[8] and NLO QCD+EW (right)



- Electroweak effects move relation **towards the data** for the **low-p_T region**
- In **high-p_T region**, EW corrections are negligible

[8] R. Gauld, *et al.* High Energ. Phys. 2017, 3 (2017)

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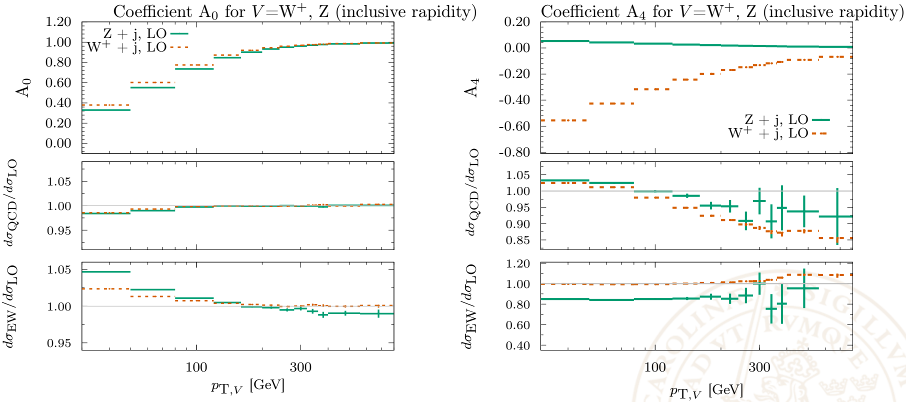
Decay coefficients for W+jet: motivation



- Direct decay coefficient measurements by CDF (1.8 TeV)[7]
- Template fits of distributions to measure W-boson mass[6]
- Improve fluctuations by an unfolding to Z+jet [6]

[7] CDF Collaboration arXiv:hep-ex/0504020
[6] ATLAS Collaboration arXiv:1701.07240

Decay coefficients for W+jet: setup

- **This project**: Calculate and combine NNLO QCD and NLO EW corrections to the angular coefficients
- **Fixed-order**: $pp \to \{e^+ \nu_e\} + j$ at 13 TeV at:

$$\text{NLO EW} := \text{LO}_1 + \text{LO}_2 + \text{NLO}_2$$
$$\text{NNLO QCD} := \text{LO}_1 + \text{NLO}_1 + \text{NNLO}_1$$

- MadGraph5_aMC@NLO (for NLO EW) and STRIPPER (for NNLO QCD) [11]

[11] M. Czakon arXiv:1005.0274

Decay coefficients for W+jet: setup

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- **Fixed-order**: $pp \to \{e^+\nu_e\}+j$ at 13 TeV at:

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$$\text{NNLO QCD} := \text{LO}_1 + \text{NLO}_1 + \text{NNLO}_1$$

- MadGraph5_aMC@NLO (for NLO EW) and STRIPPER (for NNLO QCD) [11]
- Combining NLO EW and NNLO QCD, default way (unexpanded):

$$\mathrm{A}_i^{\text{default}} = \frac{N}{D}, \tag{8}$$

- Expansion in α_s:

$$\mathrm{A}_i^{\text{exp}} = A + \alpha_s B + \alpha_s^2 C, \tag{9}$$

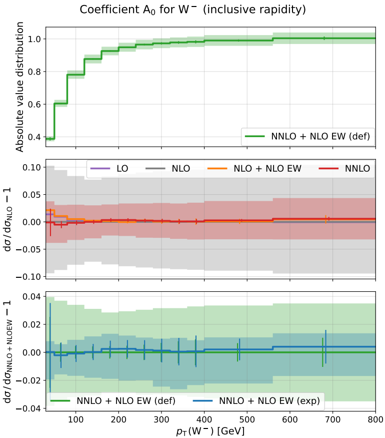
- Inclusion of NLO EW through an overall K-factor (avoids $p_T(l)$ cut dependence)

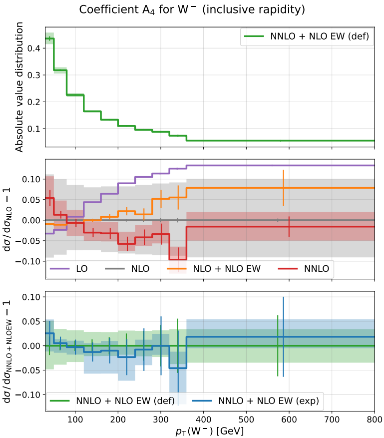
$$\mathrm{A}_{i,\text{QCD+EW}} = K_{\text{NLO EW}} \times \mathrm{A}_i, \tag{10}$$

[11] M. Czakon arXiv:1005.0274

Decay coefficients for W+jet: results, inclusive rapidity

- The coefficients A_0 (left) and A_4 (right) for W^- signature, inclusive in rapidity

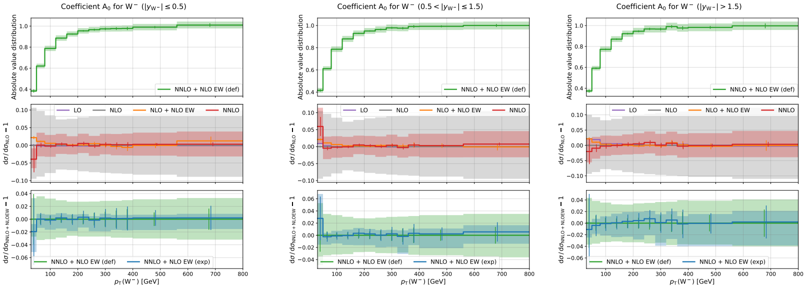




[12] M. Pellen, R. Poncelet, A. Popescu, T. Vitos. arXiv:2204.12394

Decay coefficients for W+jet: results, A_0 rapidity dependence

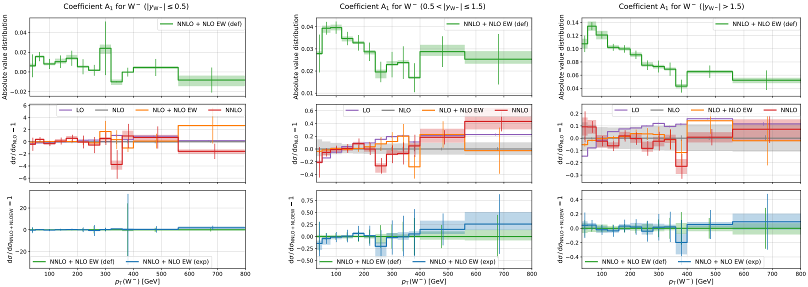
- The coefficients A_0 in various rapidity bins
- No rapidity dependence (same for A_2)
- Mid: $|y| \leq 0.5$, mid-central: $0.5 \leq |y| \leq 1.5$, forward: $|y| \geq 1.5$



[12] M. Pellen, R. Poncelet, A. Popescu, T. Vitos. arXiv:2204.12394

Decay coefficients for W+jet: results, A_1 rapidity dependence

- The coefficients A_1 in various rapidity bins
- Note: different y-scales!
- Heavily rapidity-dependent (same for A_3 and A_4)
- Mid: $|y| \leq 0.5$, mid-central: $0.5 \leq |y| \leq 1.5$, forward: $|y| \geq 1.5$



[12] M. Pellen, R. Poncelet, A. Popescu, T. Vitos. arXiv:2204.12394

Decay coefficients for W+jet: EW non-closure effect[13]

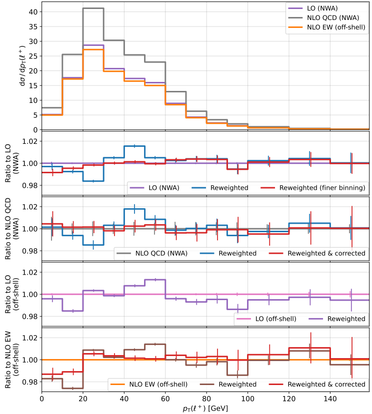
- The expansion to spherical harmonics is no longer valid when EW splittings are allowed ($1 \to 3$ kinematics)

[12] M. Pellen, R. Poncelet, A. Popescu, T. Vitos. arXiv:2204.12394

[13] M. A. Ebert, *et al.*. arXiv:2006.11382

Decay coefficients for W+jet: EW non-closure effect[13]

- The expansion to spherical harmonics is no longer valid when EW splittings are allowed ($1 \to 3$ kinematics)
- Reproduce lepton distribution ($p_T(l^+)$) with angular coefficients with reweighting
- Correct for binning effects
- Correct for NWA effects (from LO)
- NLO EW (off-shell) versus reweighted with A_i show good agreement (except first few bins)



[12] M. Pellen, R. Poncelet, A. Popescu, T. Vitos. arXiv:2204.12394
[13] M. A. Ebert, *et al.*. arXiv:2006.11382

Summary and outlook

Summary

- **Z-boson:** Negligible NLO EW corrections for the Z-boson decay coefficients in high-p_T range
- **Z-boson:** In low-p_T range, electroweak non-closure effect might be a source of error
- **W-boson:** Significant few percent effects from NNLO QCD and comparable NLO EW corrections
- **W-boson:** Very different scale uncertainty bands for expanded and unexpanded versions

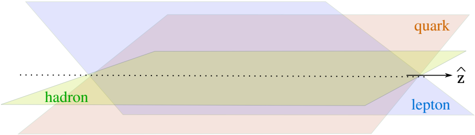
Future prospects

- **Z-boson:** Awaiting the 13 TeV results from ATLAS for Z+jet angular coefficients (reduced uncertainties?)
- **W-boson:** Resummation effects at low-p_T range for ATLAS
- Hopefully - matching to parton showers (but expected to be small)

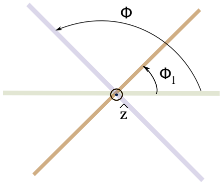
Thank you for listening!

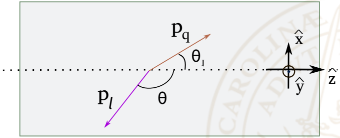
Collins-Soper frame

- $pp \to V + X \to l_1 l_2 + X$: in Collins-Soper frame[7]



- Introduce polar and azmuthal angles θ_1, Φ_1 of quark compared to the hadron plane



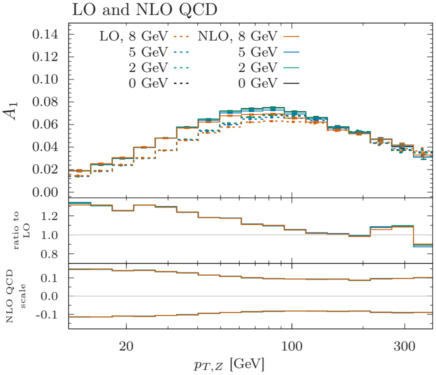


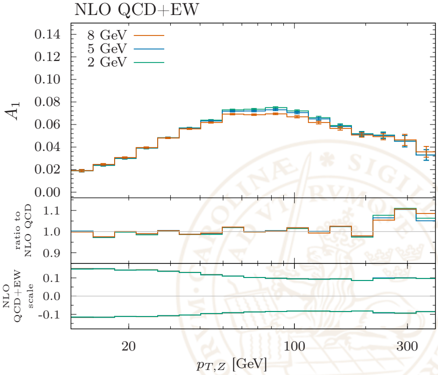
- Angles θ, Φ are the angles of the (negatively charged) lepton l^-

[7] J.-C. Peng *et al.*, arXiv:1511.08932

Decay coefficient for Z+jet: results

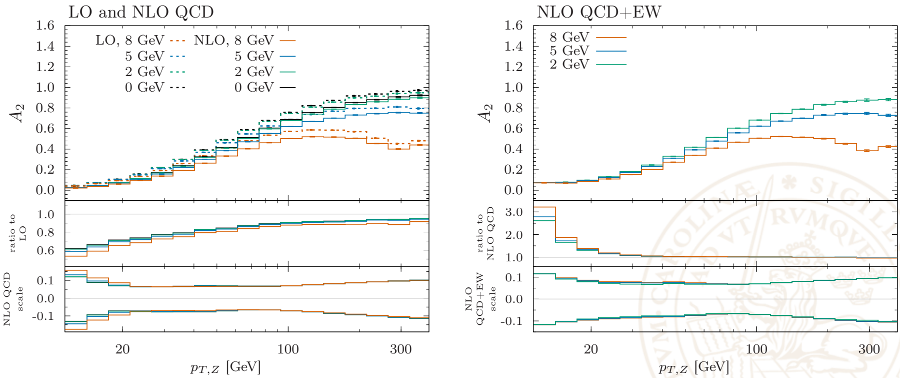
- $p_{T,Z}$-distributions for $\boldsymbol{A_1}$ at LO and NLO QCD (left) and NLO QCD+EW (right)
- Negligible electroweak corrections





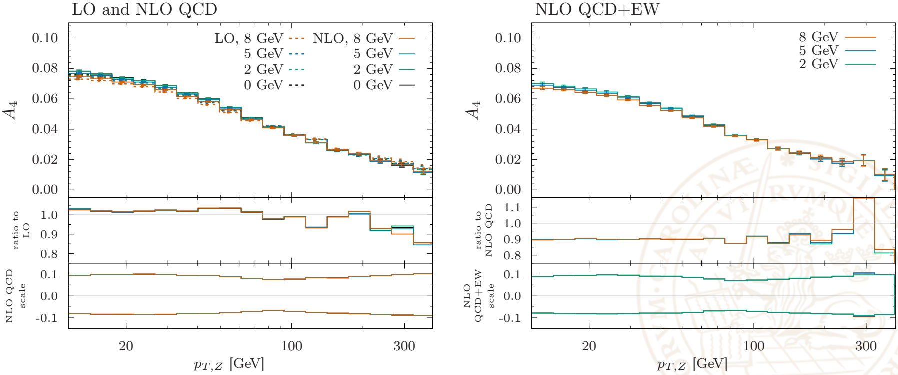
Decay coefficients for Z+jet: results

- $p_{T,Z}$-distributions for $\boldsymbol{A_2}$ at
  LO and NLO QCD (left) and NLO QCD+EW (right)



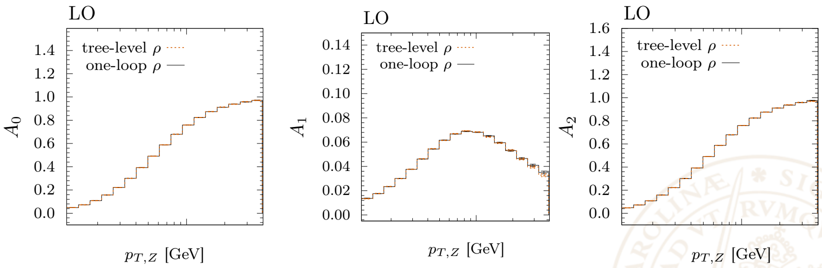
Decay coefficients for Z+jet: results

- $p_{T,Z}$-distributions for $\boldsymbol{A_4}$ at
  LO and NLO QCD (left) and NLO QCD+EW (right)
- Same -10% electroweak corrections



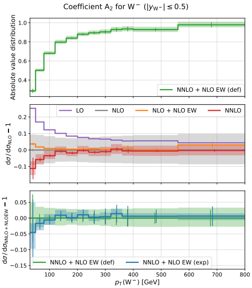
Decay coefficients for Z+jet: ρ-parameter

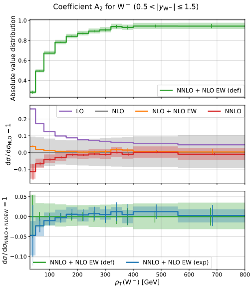
- The coefficients A_0,A_1,A_2 are not affected by the weak mixing angle

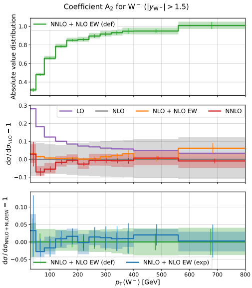


Decay coefficients for W+jet: results

- The coefficients A_2 in various rapidity bins

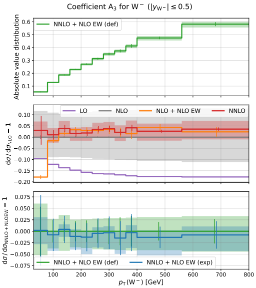


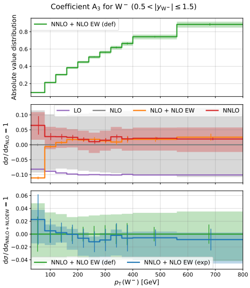


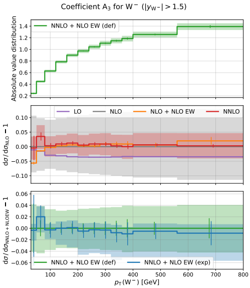


Decay coefficients for W+jet: results

- The coefficients A_3 in various rapidity bins







Decay coefficients for W+jet: results

- The coefficients A_4 in various rapidity bins